Fire Management notes

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Wildland Fire Weather

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On the Cover:

Lightning strikes such as this one in Alabama ignite about 10,000 wildland fires in the United States each year. Lightning detection and other aspects of fire weather important to the fire community are discussed in this issue.
Photo: Courtesy of Johnny Autery, Dixons Mills, AL, ©1997.

Lightning Detection and Data Use in the United States

Brenda L. Graham, Ronald L. Holle, and Raúl E. López

Each year, lightning ignites about 10,000 wildland fires in the United States (DeCoursey et al. 1983). Wildland fire managers in the 11 Western States and Alaska have routinely used near-real-time lightning detection network data to determine likely areas for new ignitions. Few of them, however, have had training in the sensor technology, location accuracy, and detection efficiency of these lightning detection networks. The intent of this article is to provide background in these areas so fire managers can make full use of this technology.

Lightning Itself

There are two types of lightning:

- Cloud-to-Ground (CG) flashes and
- Cloud discharges.

The following brief description is limited to CG lightning since it is the type that initiates wildland fires.

A CG lightning flash (commonly called a "strike" in the wildland fire community) is composed of a series of events that occur very quickly. These events are roughly as follows:

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Present lightning detection networks provide fire managers in the United States with information about potential lightning-caused wildfires. Lightning location information can also be used for other purposes such as planning for prescribed natural fire.

1) A thunderstorm cloud (cumulonimbus) becomes predominately positively charged at the top and negatively charged in the lower part (Uman 1969).
2) A typical CG lightning flash begins as a "step leader" that "jumps" about 150 feet (50 m) at a time toward the ground from the negatively charged region at the bottom of the cloud (fig. 1).
3) The step leader travels very quickly and takes about 20 milliseconds to travel about 2 miles (3 km) (Uman 1969).
4) As the negatively charged step leader approaches the ground, positively charged "streamers" respond by traveling skyward toward the step leader. Streamers typically move up from the tallest well-grounded object like a tree or building (fig. 1).
5) When the step leader and a streamer meet about 150 to 300 feet (50 to 100 m) above ground, they form an electrical channel that is about as wide as your thumb.

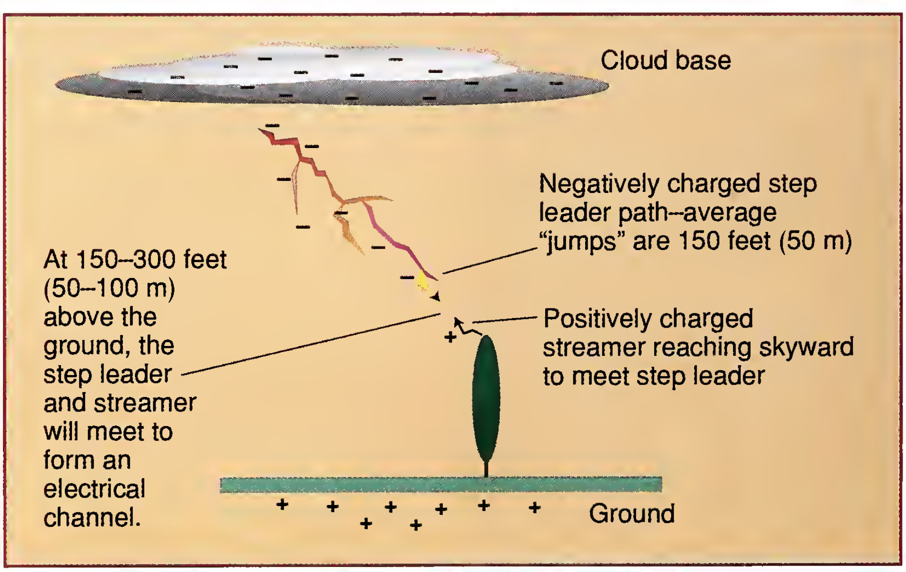

Figure 1—*A step leader jumps toward the ground and a streamer reaches from the tree to meet it.*

6) A series of electrical current surges called return strokes follows. Two to four return strokes, which have the net effect of lowering negative charge to the ground, comprise a typical lightning flash (Uman 1969). This is the origin of the term "negative lightning," which is the most common type of CG lightning. "Positive lightning" occurs when a positive charge is lowered to the ground (about 5 to 10 percent of CG flashes are positive). Figure 2 shows a common form of damage when lightning strikes a tree.

Figure 3 shows three CG flashes photographed in about 1 second by moving the camera from left to right. The first return strokes of the two main flashes are to the left; they have several branches. The left flash has seven return strokes with a single-stroke flash just to its right. The flash on the right has six return strokes.

Figure 2—*Damage to tree that was struck by lightning in New Bern, NC. Photo: Kevin Kelleher, National Severe Storms Laboratory, Norman, OK, ©1995.*

Figure 3—*Three cloud-to-ground (CG) lightning flashes over Norman, OK, photographed in about 1 second by moving the camera from left to right. Photo: W. David Rust, Norman, OK, ©1985.*

Lightning is tremendously energetic. The typical CG lightning flash carries a peak current of 30,000 amperes. In comparison, most household circuits in the United States carry 15 amperes, and a 100-watt light bulb uses about 1 amp (Uman 1971). In a fraction of a second, the air immediately around the lightning channel is super-heated to 15,000 to 60,000 °F (8,000 to 33,000 °C), which is much hotter than the sun's surface (Uman 1969). This rapid heating creates the shock wave we hear as thunder.

Most CG lightning flashes in wildland areas do not create new fires because the fuels are not exposed to high temperatures long enough for combustion to begin. However, when wildland fuels become very dry due to some environmental condition such as prolonged drought, the likelihood of ignition increases.

Technologies Used in Lightning Detectors

CG lightning flashes produce uniquely shaped electromagnetic waves that can travel great distances. Lightning detection networks are designed to use this information.

Lightning detection sensors in the United States use "direction-finding" (DF) or "time-of-arrival" (TOA) technologies. The performance of a lightning detection network is affected by the character of its sensor technology.

DF Technology. Based on traditional radio direction-finding techniques, DF technology sensors have two loop-shaped antennas perpendicular to each other. A lightning flash's magnetic field induces signals in both loops that are determined by factors such as the flash's current flow and the orientation of the lightning channel to the antennas. When the radio signal produced by a lightning flash arrives at the antenna, onsite software immediately compares the ratio of signals in the loops to identify the flash's azimuth. All azimuths from all sensors are sent to

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a central processor that uses azimuths from two or more sensor sites (triangulation) to identify the probable area of flash location (fig. 4) (Holle and López 1993).

TOA Technology. TOA technology involves an evaluation of when the electric pulse generated by a return stroke arrives at multiple receivers. To determine location, the electric pulse arrival time at each receiver site is sent to a central analyzer that computes the difference in arrival times between pairs of receivers. A plot of all the points between a pair of receivers where that time difference is possible defines a hyperbola (fig. 5). Comparisons between four to six sensors provide the optimum location of the flash. Figure 5 shows a probable flash location defined by the intersection of the hyperbolas from two receiver pairs. These receivers must be synchronized to the same dependable time source for this system to work (Holle and López 1993).

Waveform Discrimination. The electromagnetic waves sent out by lightning flashes have particular forms that sensors can resolve (fig. 6). The sensors perform onsite comparisons of detected flash waveforms with a statistically determined lightning waveform obtained from previous studies of CG flashes. If the comparison is a close match, the data are accepted and sent to the network processor. This waveform discrimination helps keep spurious noise and cloud flash signals from being reported.

Figure 6a shows some of the key features of CG lightning flashes:

- The (step) leader pulse prior to discharge,
- Shape of rise-time portion of the wave, and
- Width between peak amplitude and when the signal drops to an established threshold.

Figure 6b shows some signals from negative CG discharges. Note these waves have the same features as the one in 6a, only they are inverted because they are from negative flashes. Figure 6c shows cloud discharges, and they lack the same defining features.

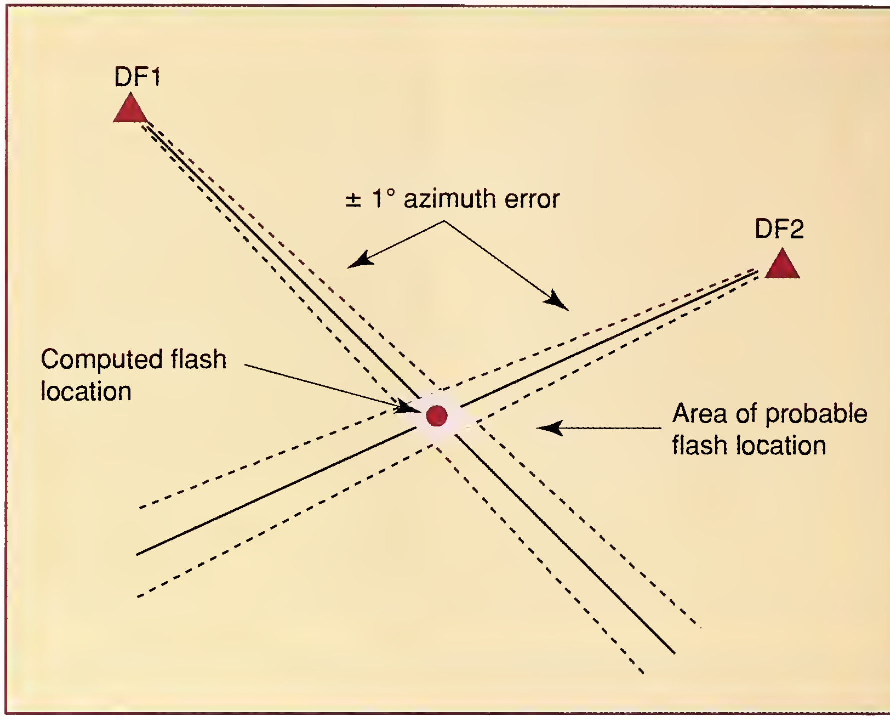

Figure 4—*Flash location by triangulation from two direction-finding (DF) antennas.*

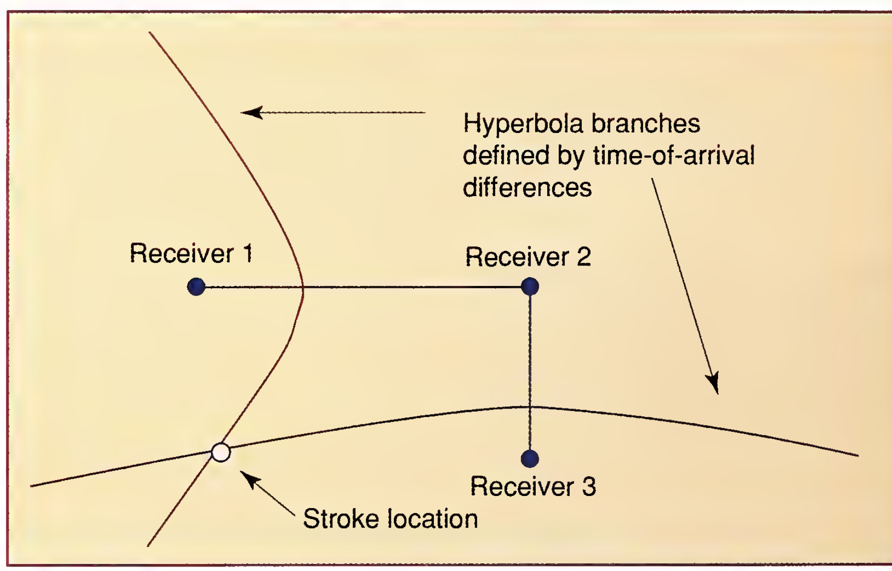

Figure 5—*Probable flash location from two pairs of time-of-arrival (TOA) receivers.*

Networks in the United States

The BLM Network. From 1976 through 1996, fire managers in the 11 Western States and Alaska received CG lightning data from the U.S. Department of the Interior's Bureau of Land Management (BLM) networks. These networks used DF technology. CG lightning data were distributed to wildland fire managers in near real time via

the BLM IAMS computer network. Beginning in 1997, the CG flash data in the 48 contiguous States will come from the National Lightning Detection Network (NLDN), but the Alaska network will remain the same for at least several more years. This change in data source will be transparent to fire managers in the 11 Western States because data distribution will continue through the existing IAMS system.

The NLDN. The current NLDN was established a few years ago in the 48 contiguous States; a private corporation (Global Atmospherics, Inc. (GAI), of Tucson, AZ*) operates and maintains this network. GAI's recently updated NLDN uses both DF and TOA technologies. The network is composed of a mixture of sensors, some sites with TOA only and some with DF and TOA together. The sensors with combined DF and TOA technology are called IMPACT (Improved Performance from Combined Technology). TOA sensors are basically a short whip antenna, and figure 7 shows an IMPACT sensor (note the loop antennas). Figure 8 shows the NLDN sensor network as of May 1996 with the type of sensor technology at each site.

The sensors using only TOA technology have limited CG flash waveform discrimination and report only the flash-arrival time. IMPACT sites use more detailed waveform discrimination and report both azimuth and arrival-time data. These data are sent to a single central

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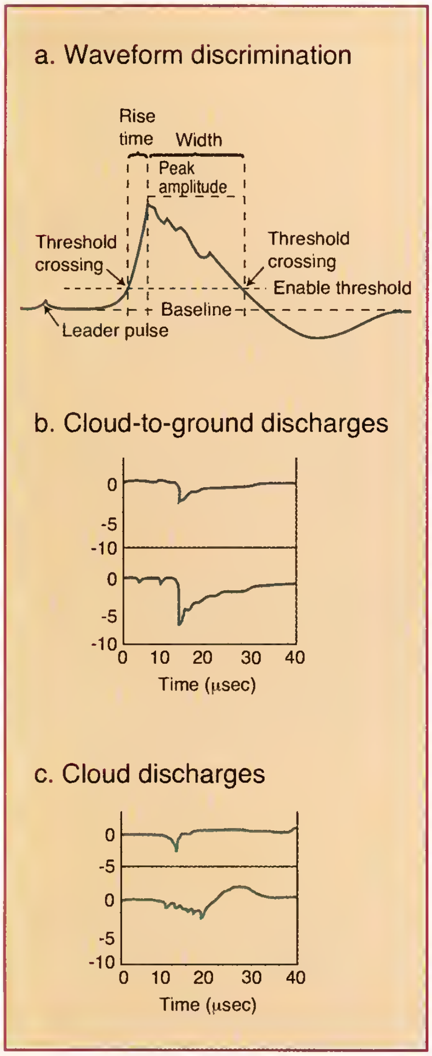

Figure 6—*a. Characteristic features of cloud-to-ground (CG) waveform, b. negative CG flashes, c. cloud flashes. (Information provided courtesy of Global Atmospherics, Inc., Tucson, AZ.)*

Figure 7—*IMPACT lightning sensor used in National Lightning Detection Network (NLDN). Photo: Ken Matesich, 1995 (courtesy of Global Atmospherics, Inc., Tucson, AZ).*

processor that resolves all the information into individual CG flashes and locations. GAI gathers, processes, and archives all the data.

Network Performance

DF sensors are subject to errors caused by topography and human-made structures near the site. Local terrain and buildings can reflect, absorb, and reradiate signals. However, once each site's errors are documented, they are corrected during data processing to minimize potential inaccuracies.

Network detection efficiency (percentage of actual CG flashes reported) is a function of sensor layout and where the CG flashes occur relative to the sensors. In some cases, CG flashes remain unreported because their signals are too weak to be received by enough sensors for calculating a location. A CG signal that passes the waveform compatibility test can still be discarded if it does not achieve a minimum signal strength threshold value. In some cases, the waveform itself may be rejected because it does not fall within the statistical CG flash profile.

Location accuracy of networks also depends on sensor layout and where the CG flashes occur relative to the sensors. Location accuracy with networks based on DF-only sensors (like the BLM networks) has been shown to vary from about .25 to 2.5 miles (0.4 to 4 km). GAI's upgraded NLDN has a location accuracy of .3 mile (0.5 km) due to its combined use of DF and TOA technologies that allows the network to determine flash location more accurately.

The BLM network detection efficiency has been around 60 to 70 percent and possibly as low as 40 percent in some areas. Networks with configurations like GAI's have a higher network detection efficiency on the order of 70 to 90 percent (Holle and López 1993). Fire managers in the 11 Western States will probably notice about 40 percent more flashes reported by the NLDN compared to the BLM network due to improvements in network performance. Reported flashes could be even greater for some areas.

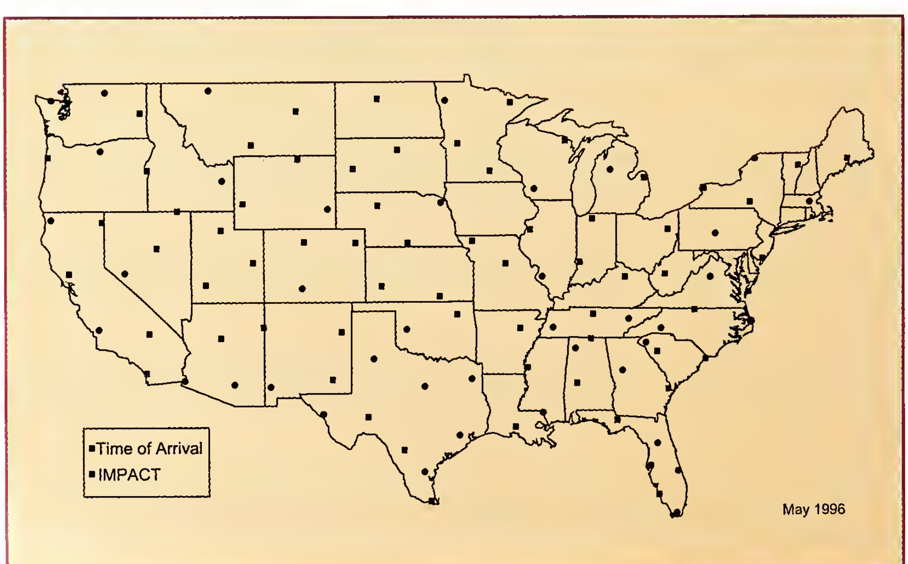

Figure 8—*NLDN sensor types and locations in the Continental United States.*

Which Flashes Cause Fires?

About 30 percent of all lightning flashes are cloud-to-ground (Krider 1994), and it would be ideal to know which are most likely to ignite a fire. Some CG lightning flashes have a long period of continuing current (fig. 9), meaning that the current is slow to decay after reaching a peak. The "blur" between some successive strokes shown in figure 3 is due to continuing current. There is some evidence that long continuing current (LCC) flashes are more likely to start fires than other CG flashes (Fuquay 1980). An LCC flash would expose fuels to heat longer, thus increasing the chance of ignition compared to an equal non-LCC flash. A limited set of data from experiments suggests that positive flashes are quite likely to have LCC, while a lower percentage of negative flashes have LCC (table 1). No lightning detection network in use today makes any distinction of current flow duration in CG flashes. GAI is conducting research in this area, however, and expects to add this capability to its network in the future.

Lightning Data Use by Wildland Fire Managers

While the most common use of lightning detection network data by wildland fire managers involves near real-time data applied to operations, historical data are also being studied. For example, the Fishlake National Forest in central Utah is using historical lightning data to evaluate the correlation between lightning and ignition occurrences over a given area. The patterns that emerge from the analysis may be valuable input for deciding which areas of the forest would be good candidates for prescribed natural fire (Chappell, per-

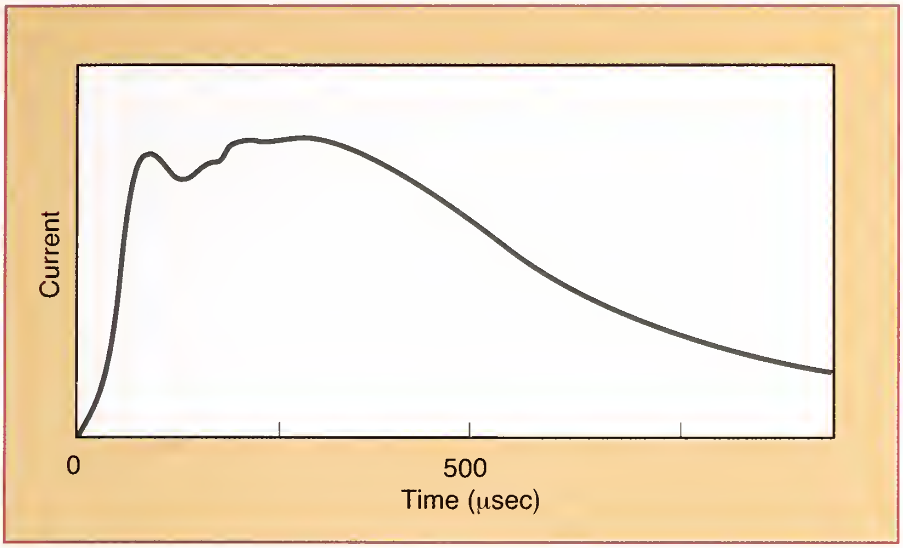

Figure 9—*Typical current waveform for a positive cloud-to-ground flash. Adapted from Uman (1987).*

Table 1—*Some characteristics of negative and positive CG lightning flashes (Anderson, adapted from Uman 1987).*

Characteristic	Negative	Positive
Percent of occurrence	90	10
Average peak current (kA)	30	35
Average number of strokes per flash	3-4	1
Percent with long period of continuing current (LCC)	20-40	50-100

sonal communication). When using historical data to develop a lightning climatology (pattern) for an area, it is important to use the longest record possible. Lightning climatology studies have already been completed for several Western States (López and Holle 1986, Watson et al. 1994, Fosdick and Watson 1995).

Conclusions

CG lightning detection network data were available solely to wildland fire managers in the Western United States and Alaska until recently. Now that the NLDN is in place, CG lightning data are available in all wildland areas of the 48 contiguous States. The combination of DF and TOA technology in the NLDN has improved detection efficiency and location accuracy. While some CG lightning flashes in your area may not be reported by a network, this situation should not have a significant impact on the value of the data. Since most thunderstorms produce several CG lightning flashes per minute, present network detection efficiencies are very adequate for most wildland fire applications.

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Safety from a Lightning Strike

Brenda L. Graham,
Ronald L. Holle, and
Raúl E. López

Everyone who works outdoors should be aware of the inherent threat of being struck by lightning. On average, at least 80 people are killed by lightning and about five times as many are injured each year. These accidents may occur due to people's ignorance of how dangerous lightning is, their inability to recognize the potential threat from lightning, or their lack of knowledge about lightning safety rules. By heeding the following advice, you can reduce the chance of death or injury when lightning is nearby.

Before Storms Develop

- Be constantly aware of how long it will take to reach safe shelter if a thunderstorm occurs.
- Observe when new thunderstorms start to develop.
- Post a lookout to observe and communicate the lightning threat.

When Thunderstorms Develop

Estimate your distance to lightning using the flash-to-bang method: Start counting seconds (one-thousand-one, one-thousand-two, etc.) from the time you see the flash until you hear the thunder. Estimate that lightning is 1 mile (1.6 km) away for each 5 seconds counted. If lightning is occurring closer than 5 miles (8 km) (or 25 seconds away), go to a safe shelter immediately, if possible. Once lightning is within 5 miles, the next flash may occur where you are, so plan to reach safe shelter before lightning occurs that close.

Lightning Nearby

When outside and far from vehicles or buildings, seek a thick grove of small trees surrounded by tall trees. **Stay away from individual trees.**

- Don't stand in an open area more than 100 yards (91 m) across.
- Don't be the highest object, such as on a ridge, rock outcropping, or roof.
- Don't be in the water or in a boat.
- Don't be near or in contact with anything taller than its surroundings that may be prone to being hit by lightning.
- Don't be near or in contact with large metallic objects such as antennas or metal fences.

The **best** option is to go inside a public building or a residence. Metal-topped buildings with stone or other nonconducting walls are **not** safe. Don't touch anything connected to the power and phone lines or plumbing pipes. The second best option is to go inside a vehicle with a solid metal top, but don't touch the sides of the vehicle.

Last Minute

If you are caught outside with lightning nearby or your hair stands on end and none of the above options are available:

- Crouch on the balls of your feet with your head down, and grasp your knees with your hands. This crouching position minimizes your contact with the ground, which can be quite conductive, especially if wet.
- Don't lie flat on the ground or touch the ground with your hands.
- If in a group, spread out so that fewer people are likely to become victims.

When Lightning Strikes

Apply CPR to anyone rendered unconscious by lightning. ■

Tracking Thunderbolts: Technology at Work

Phil Sielaff

The technology involved in the Automated Lightning Detection System (ALDS) has been evolving for over 20 years. The system currently can provide information on lightning "ground strike" activity to land managers and fire officials in real time. As a result of these two decades of experimentation, others around the world are able to use the ALDS to help them anticipate natural wildfire occurrence.

> For over 20 years, the Automated Lightning Detection System (ALDS) has been evolving; as new technology is developed, the system will continue to improve in the future.

Background for Technology Development

In the early 1970's, fire managers regularly asked for less expensive and safer ways of detecting lightning ground strike activity compared with the standard practice of flying aircraft behind storms to visually track lightning. The USDI's Bureau of Land Management (BLM) responded by developing a pilot remote system to track lightning strikes in Alaska. Since then, the BLM has extended the lightning detection network to the Western United States. (See fig. 1 for locations of the BLM's lightning detection stations in the West.)

Working with the University of Arizona, Tucson, AZ, the BLM's Office of Scientific Systems Development in Denver, CO—jointly with the Division of Communications Management at what was then called the Boise Interagency Fire Center—developed the prototype of ALDS. The initial operations in Alaska demonstrated that ALDS—when used in conjunction with National Weather Service (NWS) weather radar—could achieve significant savings in isolating "active" cells. (An "active cell" is one that is producing lightning ground strike activity.) As increased experience and detection efficiencies were attained in Alaska, the NWS began to use the ALDS to supplement weather radar to detect thunderstorm activity at long distances (outside of weather radar range).

Because of their satisfactory experiences in Alaska, the BLM decided in the late 1970's to place instruments **in** the Western United States and establish the first operational ALDS network.

The BLM next worked with a new commercial firm—Lightning Location and Protection Inc. (LLP)*—to place and operate the ALDS, supplying coverage over roughly 95 percent of the States located west of the Rocky Mountains.

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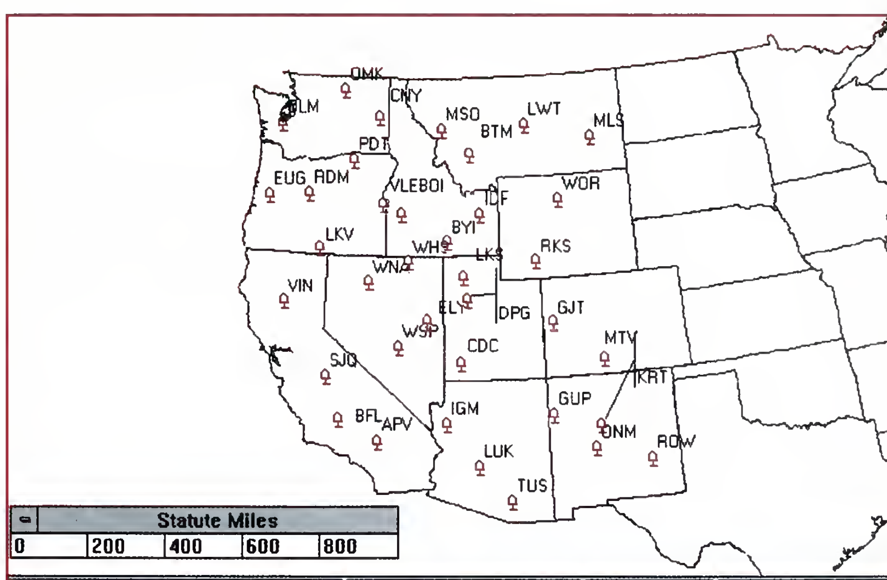

Figure 1—*Map of the Western United States showing locations of Bureau of Land Management (BLM) lightning detection stations in 1996.*

Phil Sielaff is the leader of the Remote Sensing Support Group for the United States Department of the Interior, Bureau of Land Management, National Interagency Fire Center, Boise, ID.

As we operated the early system, many other interested "observers" began to see what this network could do operationally in real time. Thus the NWS, Federal Aviation Administration, Department of Defense, Department of Energy, and many private firms began to monitor our efforts.

Network Products

Having the right information in a form that local managers can readily use for real-time fire management was the BLM's primary goal in developing ALDS. For example, figure 2 illustrates lightning strikes for 2 hours on May 14, 1996, over the Western United States. The local fire management staffs in these "active" areas have the capabilities at their respective locations to zoom in on this activity. As the local user begins to actively use the ALDS information, additional fire management information is added to the ALDS plots to provide a composite of the "big picture" at the user's particular location. Because it is clear in figure 2 that there is a great deal of thunderstorm activity near the Oregon and Idaho border, local fire managers would actively process all available data to implement action plans (e.g., move to an elevated planning level, pre-position pumper crews, dispatch reconnaissance crews).

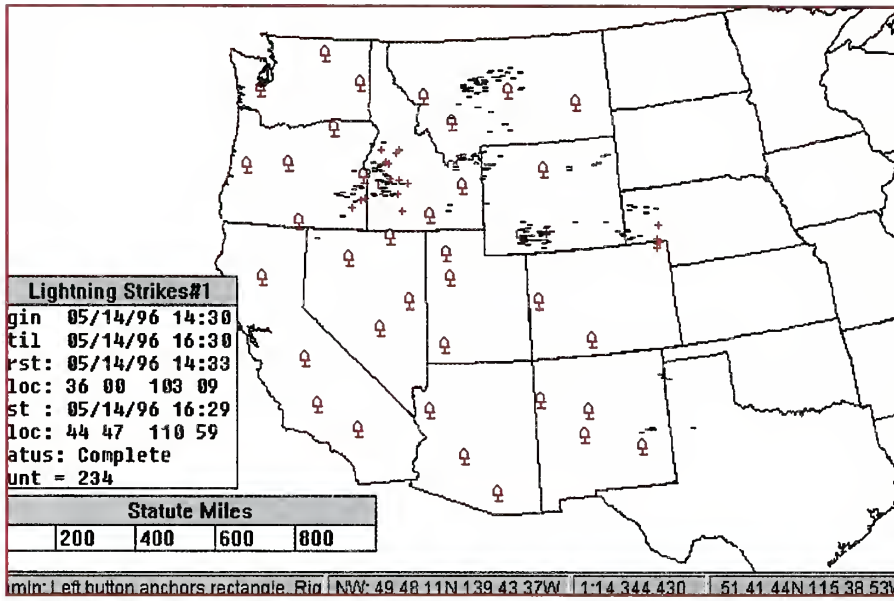

Figure 2—*Locations of 234 lightning strikes in the Western States for 2 hours on May 14, 1996.*

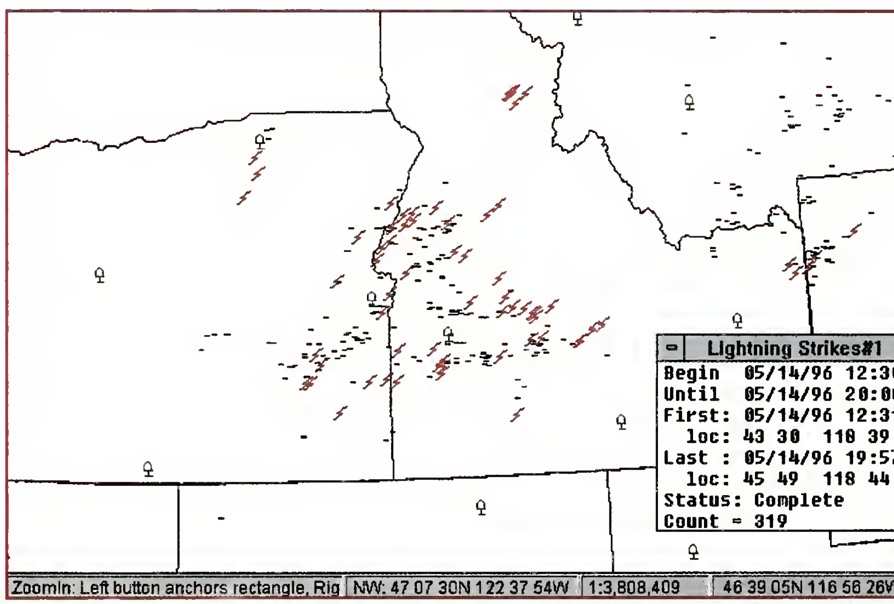

Figure 3—*Positive (red zigzags) and negative (black dashes) lightning strikes in Idaho and Oregon from 12:30 to 8:00 p.m. on May 14, 1996.*

Figure 3 shows how the BLM's lightning detection system can "zoom in" to track 319 strikes in Idaho and Oregon during 7-1/2 hours on May 14. Note that positive lightning strikes are shown with red zigzags and negative strikes with black dashes.

These types of graphics are produced in real time at each local BLM user site that has lightning ground strike activity. The process begins when direction finders (DF's) (electronic sensors) detect lightning ground strikes. Every lightning flash generates a distinct signal that travels outward uniformly at nearly the speed of light. (The movement of this signal is similar to the radiation of circles around a pebble after it is dropped in still water.) Each distinct signal is picked up by the DF's, which have specially designed antennas and electronics to measure the direction to the ground strike. The DF's determine the direction and transmit that and other information such as strike polarity and signal strength to a Position Analyzer (PA). The Position Analyzer (a computer-like device) performs numerous mathematical calculations to process incoming DF data,

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triangulates the vectors, validates the information, and then pinpoints the exact location (latitude and longitude coordinates) of each lightning ground strike. The final processed PA information is automatically sent to any authorized field user who wishes to access it.

Figure 4 illustrates more closely the 319 lightning strikes also shown in figure 3 and shows boundaries of counties.

Results of Monitoring Efforts

As a result of observing the lightning locating system and the products derived from the system, LLP and other lightning detection companies began to market and sell their systems to other government and nongovernment users. These local networks proliferated during the early and mid-1980's. The Electrical Power Research Institute, in conjunction with the State University of New York at Albany, began to consolidate all of these independent detection networks into a "national" system to supply coverage throughout the conterminous United States. As a result of these and other efforts, for the first time at the beginning of 1990, lightning data on a quasi-national basis were available from the private sector.

Looking to the Private Sector

Because of recurring costs associated with operating a large ALDS network and the prospect of having to replace older ALDS equipment, the BLM began looking to the private sector as a possible alternate source for lightning data. In 1995, the NWS, working through the Office of the Federal Coordinator for Meteorology, took the lead to consolidate all Federal users interested in procuring lightning data. As a result, a contract was awarded to Global Atmospherics, Inc. (GAI) of Tucson, AZ, to supply national lightning detection information for the conterminous United States and some maritime areas. The services provided under this 5-year contract will provide increased capabilities for the BLM and many other Federal users. Because Alaska has its own unique requirements, GAI cannot supply lightning data for that State at this time. Therefore, the BLM will continue to operate its own ALDS in Alaska.

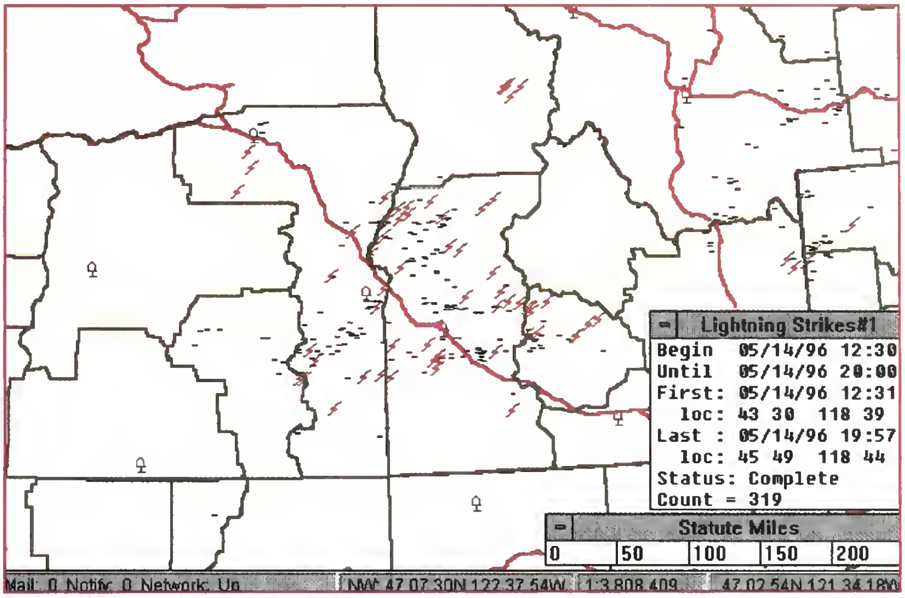

Figure 4—*Map of southwest Idaho showing county boundaries and locations of 319 lightning strikes on May 14, 1996.*

Currently, the BLM is receiving National Lightning Detection Network (NLDN) data at our National Interagency Fire Center in Boise, ID. We use the existing Initial Attack Management System/Automatic Lightning Detection System (IAMS/ALDS) telecommunications network to distribute NLDN data to the BLM real-time user community (up to 70 file server locations). Negotiations are currently underway with other USDI fire management staffs to see how they will attain data under this new contract arrangement. Under current contract provisions, the BLM cannot and will not redistribute lightning data to other Federal or State users. The only exception to this provision is if Federal or State fire offices are collocated with the BLM. Those cooperators may continue to use the data at the particular field office but cannot redistribute or broadcast the information beyond that point. (This provision can be modified if the collocated Federal or State fire office attains rights from GAI to distribute the data to its user community.)

The BLM's lightning detection efforts will continue to evolve as improvements in technology are found and implemented. Compared to our standard fire management practices of just 20 years ago, the efforts have been well worth the investment in time, energy, and money.

For more information about ALDS or NLDN data, please contact Phil Sielaff, USDI, Bureau of Land Management, 3833 South Development Ave., Boise, ID 83705-5354, telephone 208-387-5363, fax 208-387-5397, e-mail: psielaff@nifc.blm.gov ■

Current Status of the Wildland Fire Assessment System (WFAS)

Robert E. Burgan, Patricia L. Andrews, Larry S. Bradshaw, Carolyn H. Chase, Roberta A. Hartford, and Don J. Latham

The Fire Behavior Research Work Unit (RWU) of the Intermountain Research Station has been developing the Wildland Fire Assessment System (WFAS) since 1994. The WFAS will eventually combine the functionality of the current fire-danger rating system (Deeming et al. 1977) and the fire behavior system (Andrews 1986). The new system will assess fire potential across spatial scales ranging from national to site specific and time scales ranging from near-real-time to 5-day forecasts. The outputs will be useful for fire management tasks ranging from strategic planning to current fire situation analyses (Burgan and Bradshaw 1997).

Traditionally, the terms "fire danger" and "fire behavior" have described assessments of fire potential on different time and space scales. Fire danger has been evaluated routinely, at least once a day, for broad areas. Fire behavior assessments, however, are made as needed for specific sites. Both use weather that has been forecasted or measured, but fire danger—because of its routine and regular computation—requires regularly formatted and routinely available data for automated processing.

Robert Burgan is a research forester, Pat Andrews is a research physical scientist, Larry Bradshaw is a meteorologist, Carolyn Chase is a mathematician, Roberta Hartford is a forester, and Don Latham is a research meteorologist for the USDA Forest Service, Intermountain Research Station, Fire Behavior Research Work Unit, Missoula, MT.

> The Wildland Fire Assessment System (WFAS) will use the best methodology available to provide fire potential assessments for the 21st century.

Fire behavior must have weather inputs matched as closely as possible to the fire site.

Fire danger ratings have traditionally been relative values or dimensionless indexes, whereas fire behavior assessments are specific, physical descriptions of expected fire characteristics such as rate of spread, flame length, and fire intensity.

As we have been developing WFAS, our goal has been to remove the "seams" that exist between the current systems (Rothermel and Andrews 1987). For instance, our new "seamless system" will move easily from evaluating fire danger over a broad area to assessing fire behavior at a specific location.

As we develop WFAS, we will continue to resolve incompatibilities such as different sets of fuel models and equation differences. The WFAS framework will address the issue of weak linkages among current systems—fire behavior, fire danger, fire planning, fire effects, and smoke management—and help resolve the confusion that exists on proper application of current fragmented systems.

The fire behavior component of the WFAS will be based on the FARSITE Fire Area Simulator (Finney 1995) and will not be discussed here. Instead, we are focusing in this article on broad area fire assessment of the nature typically associated with fire danger rating.

Development and Implementation Plan

We are using a three-phase strategy to develop the WFAS and have defined the products and processes that will become available to clients once each stage is finished. This approach provides a natural transition from the existing piecemeal systems to a new integrated system. This development and implementation plan is, of course, dynamic. Based on user feedback and on the availability of new technology and research products, we expect the WFAS to change during development stages. The three phases and the planned schedule are as follows:

- Phase 1—1995 to 1996: Spatial display of weather and current National Fire-Danger Rating System (NFDRS) values.
- Phase 2—1996 to 1997: Improvements to NFDRS calculations.
- Phase 3—1998: Major fuel and fire modeling updates and gridded weather models.

Phase 1. In the completed phase 1, we enhanced the current fire-danger rating system with spatial dis-

plays. Fire danger and weather data are obtained from the Weather Information Management System (WIMS) and processed to produce graphical displays based on current NFDRS values. Phase 1 gives users the opportunity to view spatial displays and provides us with feedback for developing future products in subsequent phases.

Phase 2. During phase 2, improvements to NFDRS calculations will be implemented, but that system will not be completely redesigned. Because it is so important to compare the current fire danger with historical values, there will be a national reanalysis of historical data using the Fire Information Retrieval and Evaluation System (FIRES) (Andrews and Bradshaw in preparation) to calibrate the indexes. The main products developed during phase 2 will include new dead fuel moisture models and new live fuel moisture models driven by Normalized Difference Vegetation Index (NDVI) data received via satellite (Burgan and Hartford 1993). Once phase 2 is finished, WFAS will use the National Weather Service (NWS) as a primary source of weather data. Inclusion of observations from the fire weather network will be optional for broad-scale assessment.

Phase 3. During phase 3, we will use a gridded weather model to calculate fire potential over space and time. In lieu of wind observations or wind models, WFAS will use wind forecasts and estimated wind values. We will implement new fire spread, fire intensity, large fuel burnout, and crown fire models in the new system. In addition, we will use a national fuel map in the calculations. Eventually, WFAS displays will allow dynamic zooming to allow fire behavior assessments that are site specific.

Current Status

As part of the phased development and implementation, we made prototypes of several products and beta tested them during the summer of 1995; they are now routinely available. Broad-area weather and fire danger maps are produced from the fire-weather-station network as part of phase 1. As a preliminary test of phase 2 and 3 concepts, high-resolution fire danger maps are being produced using weather data from the Oklahoma Weather Mesonet. Satellite-based .6 mile- (1 km-) resolution fuel and greenness data are also used.

Broad Area Maps: National Map Prototypes. WIMS is queried for each day's fire weather observations and NFDRS components for the primary fuel model for every reporting station. Project scientists have been creating national maps on a workstation in the Fire Behavior RWU in Missoula, MT. The maps are based on a 6 mile (10 km) cell size using a weighted inverse distance-squared interpolation scheme between fire-weather-station locations. The entire process is to be transferred to the National Interagency Fire Center (NIFC) in Boise, ID, for the 1997 fire season.

Colored maps are produced depicting fire weather observations of temperature, relative humidity, 24-hour precipitation totals, and windspeed. Maps of fire danger components include the 1,000-hour timelag fuel moisture, Keetch-Byram Drought Index (Keetch and Byram 1968), and adjective class (fig. 1). In most cases, we use a five-color scheme (green through yellow to red).

In addition to collecting the fire-weather-network observations, each morning computers automatically collect data from all the North America radiosonde stations and compute a Lower Atmosphere Stability Index (Haines 1988). These data are used to create national and North American Haines Index maps (fig. 2).

Twenty-four-hour lightning strike data are obtained from Global Atmospherics, Inc.,* a private

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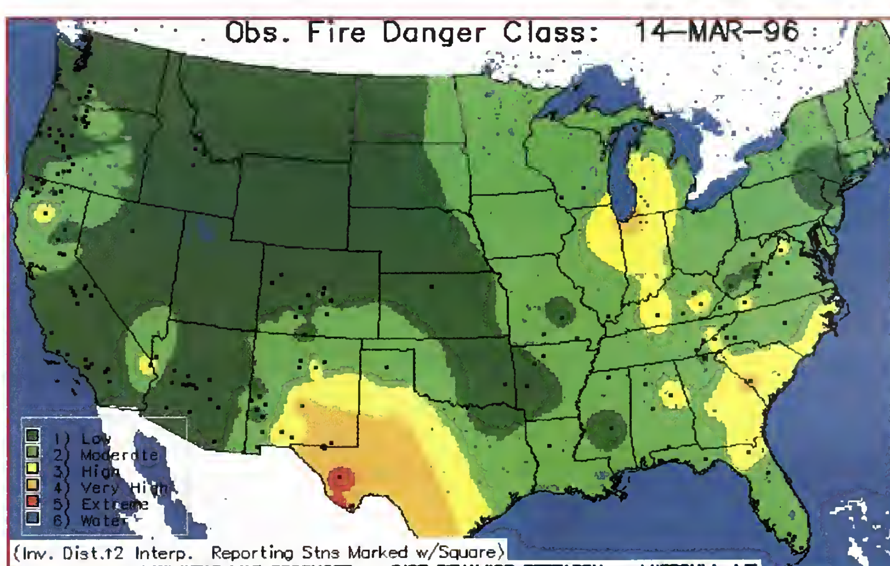

Figure 1—*Example of a WFAS product—a national fire danger map; squares indicate reporting stations. The Weather Information Management System (WIMS) provides the observed fire danger classifications that are taken directly from levels defined for each station.*

company, and overlaid on either a lightning ignition probability map or a fire danger class map. The lightning ignition probability is calculated as a function of the 100-hour timelag fuel moisture and/or duff depth (Latham and Schlieter 1991).

A four-panel vegetation greenness map derived from data obtained by satellites portrays visual and relative greenness (Burgan and Hartford 1993) as well as departure from average greenness (Burgan et al. 1996) and experimental live shrub moisture (fig. 3). These maps have a .6 mile (1 km) spatial resolution and are updated weekly.

The broad area maps are distributed as Graphics Interchange Format (GIF) files over three networks. They are uploaded to the WFAS directory in WIMS, mailed as a Data General dumpfile to the NIFC in Boise, ID, and the Northern Rockies Coordinating Center in Missoula, MT, and posted on the USDA Forest Service's Internet Home Page (www.fs.fed.us/land/wfas/welcome.html).

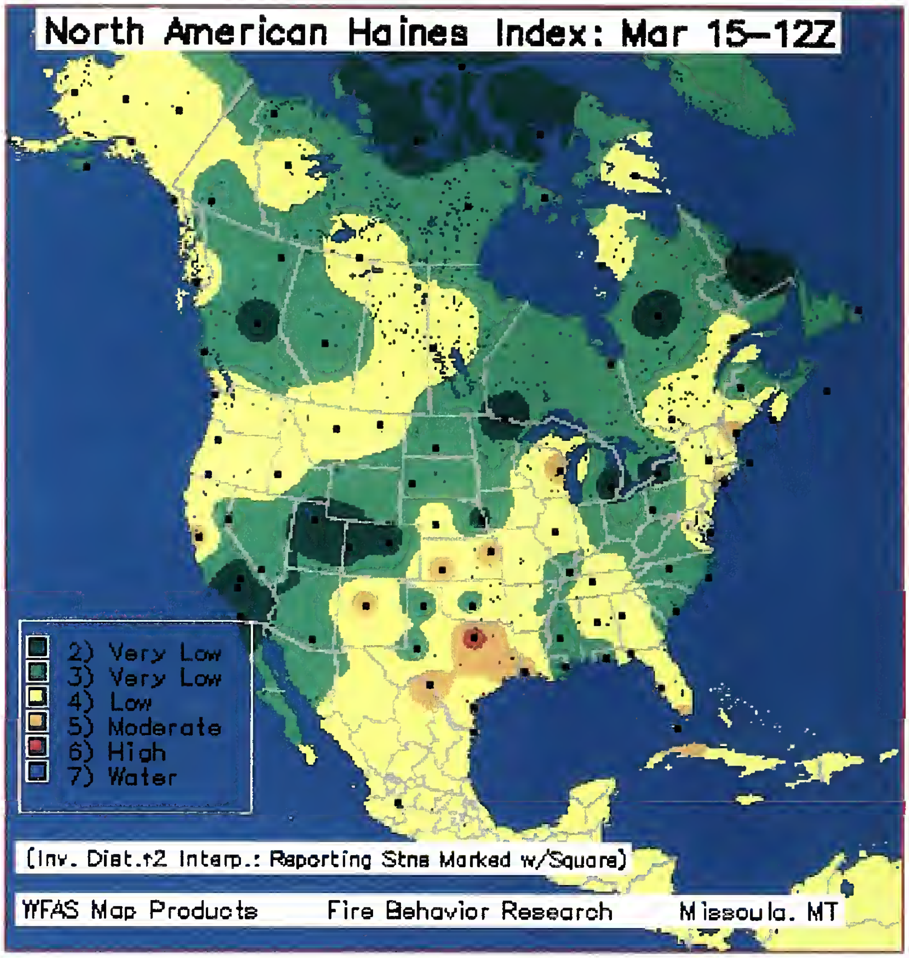

Figure 2—*Another WFAS product—a map of North America using the Haines Lower Atmospheric Stability Index (LASI) (Haines 1988). Weather data are obtained from all radiosonde stations.*

As a result of our current experience with the maps, we make the following evaluation:

- **Station Density and NWS Weather Streams.** The higher station density in the Western United States facilitates reasonable broad area maps of fire danger and fire weather elements. The lower station density in the Central and Eastern States leads to obviously bogus interpolated fields. This highlights the need to use NWS data in the broad area component of WFAS.
- **Keetch-Byram Drought Index (KBDI).** Only about 10 percent of the reporting stations have correctly cataloged annual precipitation values, a requirement for correct computation of the KBDI. The station density for the KBDI map is generally very low, therefore the map is quite unreliable on a national basis. This situation could be resolved if fire managers would enter the average annual precipitation into their WIMS weather station catalogs.
- **Coloring the Maps.** The daily fire danger adjective classes are taken directly from the WIMS computation for each station, based on the fire danger index defined by the station, number of staffing classes, and staffing level values cataloged for each station's priority-one fuel model. About 90 percent of the stations cataloged in WIMS use the burning index (BI), and the rest use the energy release component (ERC) to set their adjective class. Groupings for the five classifications on the weather maps were based on our perception of reasonable thresholds. Experience has made it clear that we imparted a western (arid) bias. "Critical" relative humidities in the Eastern States and Upper Midwest, for example, were not reflected correctly in the color code. More analysis (using FIRES) is required to delineate regional threshold values for fire weather elements.

High Resolution Maps: The Oklahoma Prototype. The high resolution NFDRS style fire danger map is represented by the Oklahoma fire

*The use of corporation names and/or their products is for the information and convenience of the reader and should not be misconstrued as an official endorsement by the U.S. Department of Agriculture or the Forest Service.

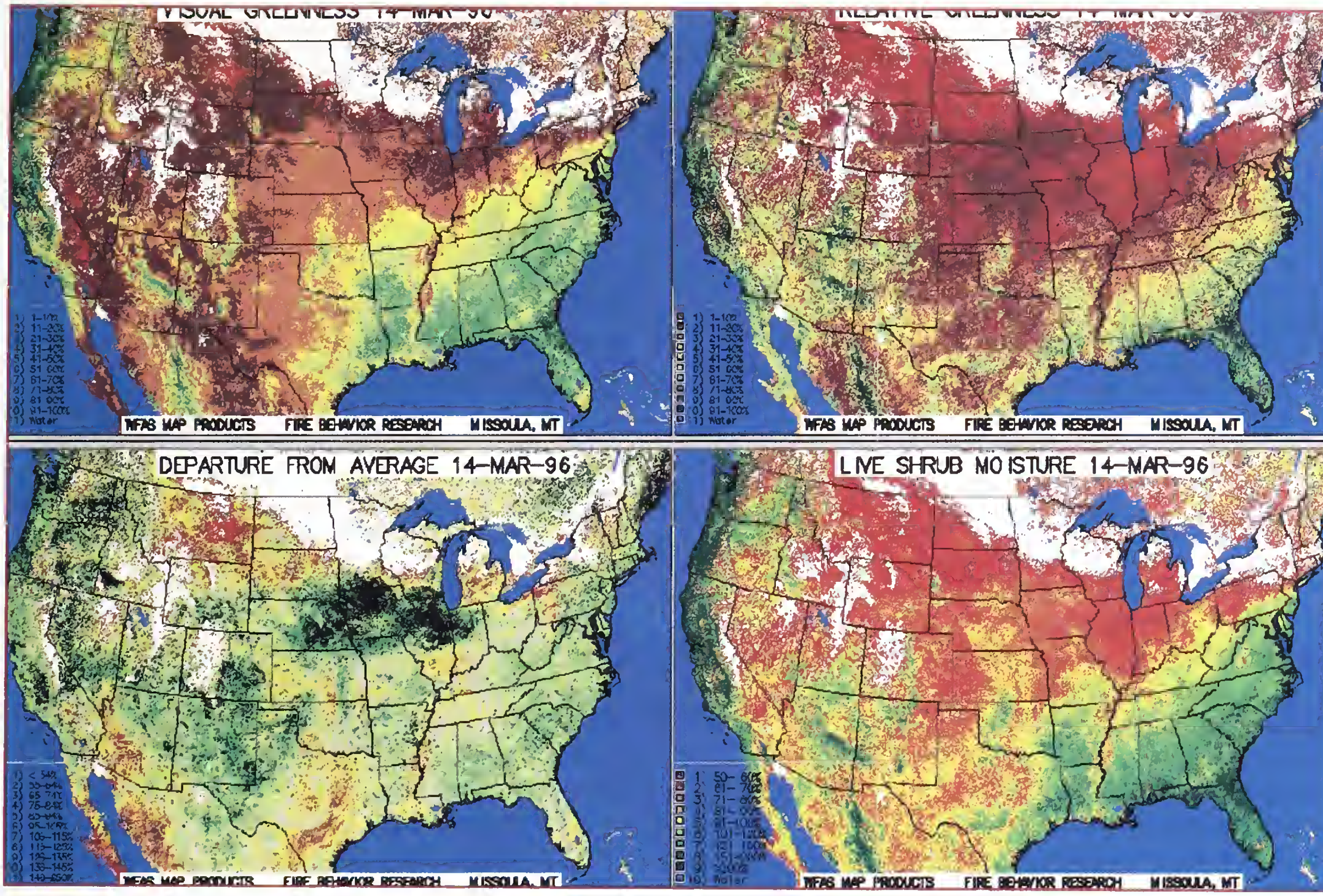

Figure 3—*Satellite data is used to produce this WFAS product—a four-panel map that portrays visual and relative greenness (Burgan and Hartford 1993) as well as departures from average greenness and experimental live shrub moisture. Vegetative greenness maps, which are updated weekly, have a .6 mile (1 km) spatial resolution.*

danger system. This system is described by Crawford (1993) and Carlson et al. (1996). Also consult Burgan and Bradshaw (1997) in this issue of *Fire Management Notes*.

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WFAS Requires a Variety of Weather Information*

Robert E. Burgan and Larry S. Bradshaw

As the Fire Behavior Research Work Unit (RWU) of the Intermountain Research Station has been developing the Wildland Fire Assessment System (WFAS) (see Burgan et al. 1997 in this issue of *Fire Management Notes*), it has been abundantly clear that weather inputs are the most difficult challenge in the system's development. In this article, therefore, we discuss required weather inputs to the WFAS in terms of weather parameters and temporal and spatial resolution. We also describe briefly a system that produces fire danger maps four times daily at a .6 mile (1 km) resolution for the State of Oklahoma and present it as an early step in the development of the WFAS.

WFAS Definitions and Attributes

Fire potential in WFAS is used in a generic sense to refer to assessments (at whatever time and spatial scale) that fit the context of the following discussion. **Fire danger** and **fire behavior** are terms used to describe assessments of fire potential on different time and space scales. **Fire danger** is evaluated routinely—at least once a day—for broad areas. **Fire behavior** assessments, however, are made for specific sites as needed.

> "The single largest challenge to building and operating the Wildland Fire Assessment System (WFAS) is collecting, processing, and archiving weather data."

With the attributes already in place as well as those planned for the WFAS, the system will:

- Require minimal data from user,
- Emphasize map and graphical outputs,
- Provide multilevel resolution inputs and outputs,
- Reflect diurnal weather variations,
- Provide "hooks" to related models (e.g., smoke dispersion and fire effects),
- Be oriented toward workstations and PC's,
- Simulate fire characteristics,
- Be operable in the field,
- Relate current to historical conditions,
- Forecast fire potential and probabilities on national to local scales, and
- Display inputs, outputs, and intermediate products.

Weather Data

The WFAS is being designed to provide maximum information to the user with minimum interference to daily work schedules in field offices. We expect that the National Weather System's (NWS) weather stations will provide a stable "minimum set" of weather stations for *broad scale* (national) fire potential assessment, but the WFAS will also use weather data collected by various agencies (e.g., USDA Forest Service, USDI Bureau of Land Management and National Park Service, States) as much as possible and include local area refinement of fire assessments. For broad scale assessments, we hope to make use of new technology available from the NWS modernization project—technology that is not likely to be available from agency-operated units. Thus two major challenges for national level fire danger assessment are 1) how to make the best use of new NWS products and 2) how best to use varying agency data as a supplement to NWS data.

As the area of interest focuses from national to site specific, we expect that Remote Automated Weather Stations' (RAWS) data or other agency-collected weather data will be used to assess specific fire events.

Capability for Regular Updates

Fire danger has traditionally focused on the "worst case" scenario

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by using 1 or 2 p.m. (local time) weather observations. Automated weather observations and satellite data provide an opportunity to assess fire danger throughout a day. Improved temporal resolution of weather data would provide fire managers with more timely information about fire potential, perhaps alerting them to problems such as severe conditions developing late in the day or poor moisture recovery at night.

Fire behavior updates could make use of weather data updates every 4 to 6 hours, but spot weather forecasts generated "on-demand" for a fire area will still be required. Fire researchers are working with the NWS to conduct weather modeling tests to determine both if gridded data can be refined enough to be useful for areas as small as fire sites and how fire weather forecasters will interface with WFAS.

Archiving Data

Traditional fire danger systems have long had some capability to relate current fire potential conditions to historical conditions. Displaying historical data infers that major decisions will have to be made concerning what weather data to archive and how to both archive and make that data available to users. It does not seem prudent to rely on the NWS to archive weather data for the WFAS because 1) it would likely have to be purchased from them, 2) it would not be "on line," 3) it probably would have to be reformatted before it was usable, and 4) it would not be under the control of WFAS managers. Therefore, a procedure must be devised to enable WFAS to "grab" data to archive for later computing of current fire danger.

Forecasting Fire Potential

Although fire potential estimates will be updated during the day, fire weather forecasts must be made available for as far in the future as they can be reasonably relied upon. This is expected to be a maximum of 3 to 5 days. Some measure of forecast reliability will be necessary. The specific measure and means of producing and displaying it will have to be discussed with the NWS.

National scale products will have to rely upon nationally available weather products. We do not expect that personal interpretation by fire weather forecasters will occur at this scale. As the forecast area decreases and one begins to look at site- and time-specific situations, it is less likely a weather station will exist within the area of interest. If the forecast area is small enough, there will not be any weather observations taken within it unless special provisions are made. Therefore forecast weather parameters for fire behavior predictions will most likely have to come from spot forecasts.

Data Displays

Although it is natural to focus on the final fire potential outputs, it is likely fire managers will want to see some of the raw inputs and intermediate products as well. For example, the NWS should provide satellite images and graphical products showing weather conditions such as cloudiness, the location of fronts, temperature maps, and wind graphics. Fire managers will also want to view such graphics as fuel moisture or drought maps, fire potential maps, and lightning location maps generated by WFAS. Discussions with the NWS and fire managers will help determine which inputs and outputs the WFAS will display.

Weather Summary

The single largest challenge to building and operating the WFAS is collecting, processing, and archiving weather data. The following describes our current assessment of weather needs, subject to review and change as development continues. Required weather parameters for broad area fire potential assessments are 1) temperature, relative humidity, solar radiation, precipitation amount and possibly duration, windspeed, and wind direction—all near ground level, 2) moisture, temperature, and stability of the lower atmosphere, and 3) cloudiness, lightning activity, and location of weather fronts. With the possible exception of windspeed and wind direction, these inputs should be obtained four times per day to help track diurnal fire danger changes and provide input to fuel moisture models. These data should be available on at least a 19-mile (30-km) grid for the Continental United States, with a 6-mile (10-km) grid being much preferred. These weather parameters must apply to the near-surface zone within which fires burn and be adjusted for slope, elevation, and aspect. We hope that the NWS will be able to make these adjustments.

Windspeed and wind direction are very difficult to project realistically to a high resolution over large geographic areas, but it would be very helpful to obtain this information in a relatively broad spatial and temporal context at the least. These two inputs need to be defined quite specifically for fire behavior applications to be site and time specific. Depending on the capabilities of mesoscale wind models, it may be

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necessary to rely on forecaster or user inputs of windspeed and wind direction for local areas.

For the time of highest fire danger, which varies regionally, 24-hour forecast data of fire danger should be provided at least once daily, and 3- to 5-day forecasts should also be updated daily for the Continental United States. All weather data should be adjusted for the effects of mountainous terrain and/or marine influences.

Outputs

Low Resolution Outputs. WFAS products that are user accessible will come in the form of:

- *Primary maps*, the lowest resolution information displays. The maps will provide the most processed "overview" data. A user should be able to click a button and view one of these maps. Examples include lightning occurrence and energy release component maps.
- *Intermediate product maps* that display underlying information are being considered. Examples of such maps are a cloudiness map, Haines Lower Atmospheric Stability Index (Haines 1988), windspeed, wind direction, weather fronts, and vegetation greenness.
- *Non-map graphics* that display information relating to the conditions of specific points or areas, such as weather station locations, ranger districts, or national forests. Examples are the fire characteristics chart and seasonal fire potential graphs.
- *Alphanumerics*, which are the actual numbers that underlie the various map and graphic outputs (e.g., energy release component, burning index, greenness) at any location for any of the primary or intermediate maps.

High Resolution Outputs. High resolution outputs require site- and time-specific assessments of fire behavior characteristics such as flame length, spread rate, and fire intensity. Such assessments would benefit greatly from 6-hourly updates of forecast weather conditions at spatial scales of .6 mile to 33 yards (1 km to 30 m). Fuels and terrain data should be presented in a similar spatial scale. Because it is unlikely that gridded weather data can be obtained at these scales, provisions will have to be made for direct weather inputs by fire weather forecasters and temporary RAWS. The fuel, weather, and terrain data will be processed in a fire simulation system to model fire behavior and location of problem fires over the next 24 hours. Planned outputs include maps of projected fire location and intensity, plotted either planimetrically or over terrain.

Calculating Fire Danger Maps for Oklahoma

The primary inputs to a mathematical model for calculating fire danger are fuels, weather, and topography. See figure 1 for a .6 mile- (1 km-) resolution fire fuels map for Oklahoma. Because Oklahoma is relatively flat, elevation data are not used for their fire danger calculations. However, elevation data are available for the conterminous United States at a .6 mile (1 km) resolution. A high resolution weather network is rare, but the University of Oklahoma (Crawford 1993) is operating one for Oklahoma. Our RWU is cooperating with the university to use weather observations from their mesonet to calculate fire danger for the State. One weather station in each county has been selected to represent the weather for that county. Figure 1 combines weather stations and fuel models for that State. Because the topography in Oklahoma is flat, the entire State can be included in a single class (0 to 20 percent slope).

The process of calculating fire danger maps is done on a pixel-by-pixel basis. First, weather data from the mesonet stations are used to calculate all the dead fuel moistures (1, 10, 100, and 1,000 hour) associated with each weather station. The dead moistures calculated from composites for a weather station are assigned to all pixels within the county in which the weather station is located. These moistures are saved in a separate data file.

Live herbaceous and shrub moistures are calculated for each pixel as a function of the relative greenness index, which is derived from the Normalized Difference Vegetation Index, which is in turn calculated from weekly composites of Advanced Very High Resolution Radiometer Data (Burgan and Hartford 1993). For the fire danger calculations in figure 2, three input map layers are referenced: 1) a map that identifies the county each pixel is in, 2) a Relative Greenness map for calculating live fuel moistures, and 3) a fuel model map consisting of a fuel model number for each pixel. For each pixel, the county map layer is used to determine the weather station representing that pixel (to access dead fuel moistures); the fuels map layer is used to identify the fuel model for that pixel; and the Relative Greenness map layer is used to calculate live fuel moistures by pixel. The rest of the calculations proceed as in the current fire-danger rating system. However, rather than the outputs being a table of

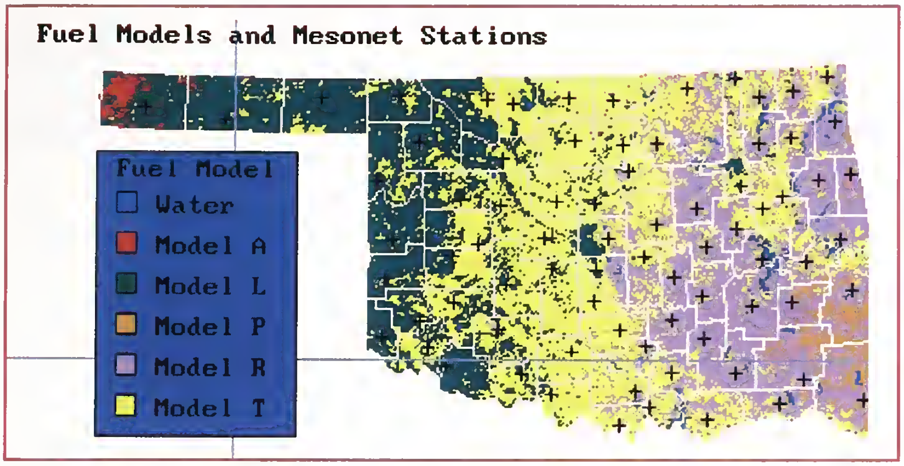

Figure 1—*NFDRS fire fuels map and partial Oklahoma Mesonet weather station network. Crosses indicate each county's weather station.*

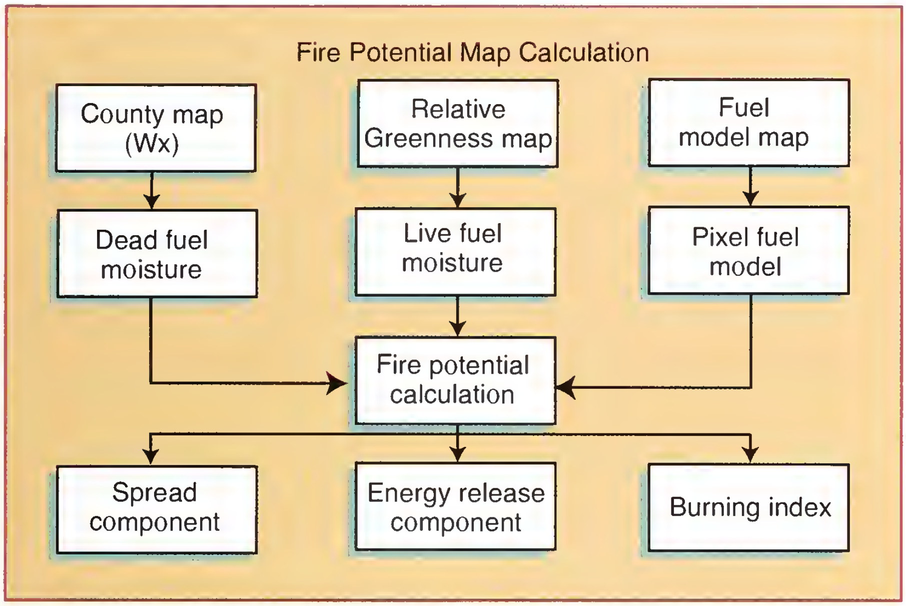

Figure 2—*Flowchart showing how weather, greenness, and fuel model maps are used to calculate fire potential, which is displayed as spread component, energy release component, and burning index maps.*

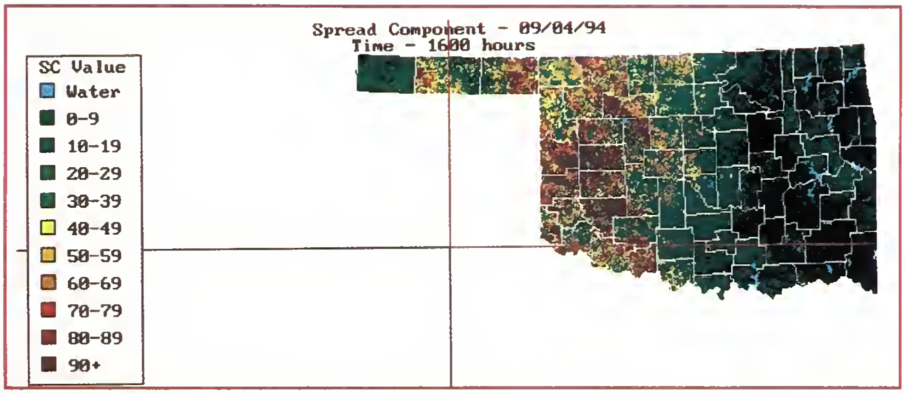

Figure 3—*Fire potential (danger) map for Oklahoma using the spread component. Note the even gradation of fire danger across county boundaries.*

fire danger indexes printed on paper for individual weather stations, they are multicolored maps of fire danger (spread component) at .6 mile (1 km) resolution for the State (fig. 3). An interesting aspect of the final fire danger map is that it shows even gradation of fire danger across county boundaries, in spite of the fact that all the pixels in each county have the same dead fuel moisture values. This occurs because of the .6 mile (1 km) spatial variability of the fuel model map and the live herbaceous and shrub moisture maps. Such maps can be produced at hourly intervals.

While this process works for Oklahoma, extending the process to mountainous terrain will require additional research. Methods are required to adjust the weather inputs for the effects of slope, elevation, and aspect.

The Oklahoma effort shows that calculation of .6 mile- (1 km-) resolution fire danger maps is feasible, even without weather data at that resolution. The next step is to use NWS gridded data to produce a similar map for the conterminous United States.

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High Resolution Fire Weather Models

Francis M. Fujioka

The next generation fire danger and fire behavior system envisioned by the Forest Service (see Burgan et al. 1997 and Burgan and Bradshaw 1997 in this issue of *Fire Management Notes)* will assess fire potential across a broad spectrum of space and time. At the incident level, fire behavior models will require detailed descriptions of the spatial and temporal variations of weather in the area of the fire. Burgan and Bradshaw (1997) suggest that high resolution fire behavior simulations ". . . would benefit greatly from 6-hourly updates of forecast weather conditions at spatial scales of .6 mile to 33 yards (1 km to 30 meters)." By spatial scale, they imply the distance between the points of a rectangular grid on which weather, fuel, and terrain conditions are available for fire behavior simulations. They write: ". . it is unlikely that gridded weather data can be obtained at these scales," but this paper is cautiously optimistic that we are closer than expected to high resolution fire weather models.

What Is a Fire Weather Model?

For the purposes of this article, a fire weather model is a scientific, computerized method of describing spatial and temporal variations of weather. The primary weather variables of interest for fire behavior modeling are the near-surface values of wind direction, windspeed, relative humidity, temperature, solar radiation, and precipitation amount. All of these can be simulated in a fire weather model, some more accurately than others. In meteorology, a fire weather model is described as *mesoscale*, in reference to the particular spatial scale of the atmospheric process it simulates (for example, see Orlanski 1975). Mesoscale models are typically used to simulate convective systems (e.g., storm events) and local circulations (e.g., sea breeze, winds over complex terrain). They may be driven by synoptic scale weather models that describe large atmospheric circulations up to the planetary scale. Synoptic scale models provide the national weather maps seen in newspapers and on television. Mesoscale modeling applications are not so routine, but they have recently included the analysis of fire weather.

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"A computerized fire weather model coupled with a synoptic model is a powerful means of describing the weather part of the fire environment."

The Need for a Fire Weather Model

A fire weather model is needed to provide a scientific, comprehensive spatial and temporal description of the near-surface atmospheric conditions that influence the fire environment. The model output should be in a coordinate system coregistered with the fuels and terrain data so that fire behavior calculations can be obtained over the area of interest. A mesoscale model based on the physics of atmospheric processes ensures that the spatial distribution and transformation of fire weather variables are generated methodically and consistently. The model should also incorporate large-scale effects of synoptic systems that are present, because generally, weather conditions on a local scale are driven by large-scale weather. A computerized fire weather model coupled with a synoptic model is a powerful means of describing the weather part of the fire environment.

Recently, three research groups conducted independent fire weather modeling experiments that portend the future of fire weather analysis and forecasting. The first compared a fire weather model with corresponding data from a high density weather station network. The second experiment simulated weather on Storm King Mountain during the tragic 1994 fire. The third experiment coupled a weather model and a fire behavior model so that the fire influenced the weather and vice versa.

The Maui Vortex

Wildfires in Hawaii are smaller on average than those in the other

Western States but are of no less concern to local fire managers. Fire weather conditions in Hawaii are unique compared to weather in the other States. On the island of Maui, a local circulation feature called the Maui vortex, or Maui eddy, can change the wind direction by 180 degrees within a few miles, significantly affecting the behavior of potential fires. The vortex is also known to trap ash and smoke issuing from pre-harvest burning of sugar cane in the central valley of Maui (Schroeder 1993), thus degrading air quality.

We used a mesoscale model developed over a period of years at Colorado State University to simulate the weather conditions over Maui in July 1988 (Ueyoshi et al. 1995). Called RAMS (Regional Atmospheric Modeling System), the model incorporates the physical laws governing atmospheric processes. In this study, we calculated—at 10-second intervals—winds, temperature, and relative humidity at points spaced 1.2 miles (2 km) apart in a rectangular grid measuring 67 miles by 55 miles (112 km by 92 km) (fig. 1). The short time step is necessary to preserve the numerical stability of computerized methods used to solve the model's underlying equations. Vertical variations are also captured at 23 levels of a terrain-following coordinate system. The model can thus simulate important fire weather effects such as inversions, precipitation, and momentum transfer between layers of the atmosphere. Model simulations, however, should be checked against the real world conditions they represent whenever possible. We compared our simulations with weather data from remote automatic weather stations deployed by a sugar plantation in the central valley of Maui.

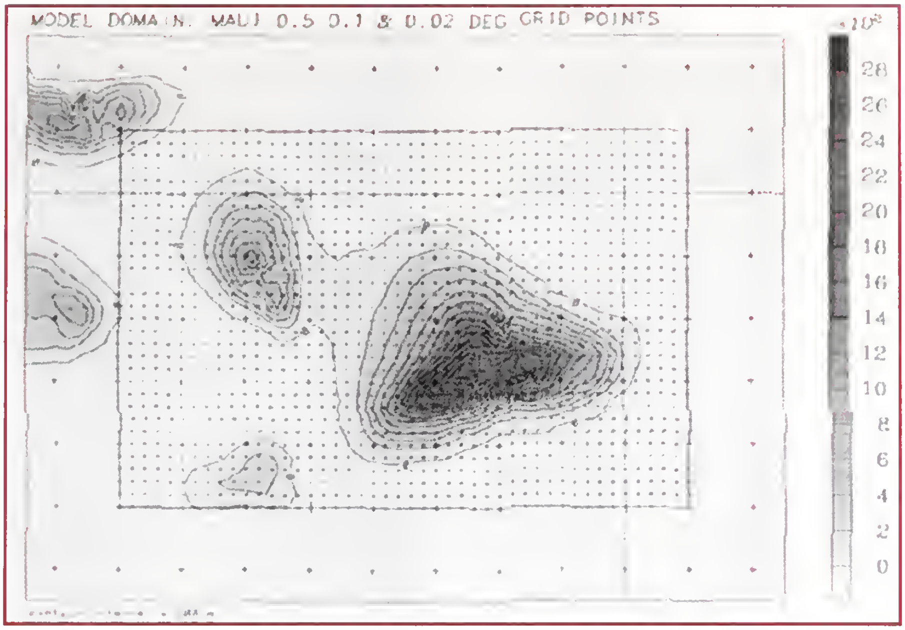

Figure 1—*Map showing the high resolution grid used in the Maui fire weather simulations (Ueyoshi et al. 1995). The grid points located at the origins of the wind vectors are 1.2 miles (2 km) apart.*

The plantation uses weather information to determine when the sugar cane can be burned without significant air quality deterioration in sensitive areas. In July 1988, the weather stations lay in that part of the vortex where average windspeeds apparently were greatest.

We found that the mesoscale model frequently overestimated windspeed by as much as 7 mi/h (3 m/sec). The model errors were larger at night and early morning than they were during the day. The model did not reproduce the diurnal range in windspeed that actually occurred, but it seemed to be in phase with the observed windspeed oscillation, except near the center of the vortex. There, the peak in the average observed windspeed lagged behind the average model windspeed by approximately 4 hours. Consequently, the model underestimated the average windspeed during most of the afternoon hours. In all cases, the model wind direction was in fairly good agreement with the observed wind direction.

An intriguing feature of the fire weather simulations was the behavior of temperature and relative humidity in the lee of the ridge line extending northward from the summit of Mt. Haleakala, the large shield volcano that dominates Maui's topography. The mesoscale model showed that, as the trade winds descended from the ridge and turned south from their westward trek, the layer of air immediately above the surface layer became warm and dry, apparently due to the spreading and sinking of air as the flow accelerated southward on the western side of the vortex. The combination of warming, drying, and accelerating air flow can invigorate a fire in this area, if this layer descends to the level of the fuels.

The mesoscale model simulations provided details that we have not seen before, but the spacing horizontally (1.2 miles or 2 km) and vertically (260 feet or 80 m in the lowest layer) is probably still too coarse. The Maui model also needs

Continued on page 24

a better specification of the surface roughness, vegetation, and soil types.

Storm King Mountain Simulation

Fire weather models can be used to study historic fires. Scientists at the Los Alamos National Laboratory applied the RAMS mesoscale model to simulate weather conditions that occurred on Storm King Mountain on the afternoon of July 6, 1994. They used a grid with points spaced 165 feet (50 m) apart in preparation for a subsequent fire behavior simulation (fig. 2). At this grid resolution, the model's computing requirements are excessive for all but the most powerful machines. At the initial stages of the Los Alamos simulations, 1 hour of simulated weather required 35 hours of computing time on a relatively high-speed Unix workstation. Since then, a version of the model code has been developed for parallel processors—computers with multiple processing units, each working on a portion of the model calculations. This has brought the computing time for a 1-hour simulation down from 35 hours to 1.5 hours and is likely to shrink the ratio even further (Bossert 1996). The improvement in computing performance brings this mesoscale modeling code into the range of feasibility for fire weather prediction.

Figure 2—*Simulated wind field in the South Canyon Fire area on the afternoon of July 6, 1994 (from Bossert 1996). Distance between the bases of adjacent vectors is 165 feet (50 m). Vector length is proportional to windspeed.*

The Interaction Between Weather and Fire

A significant recent development in fire modeling is the coupled atmosphere-fire model, which simulates the feedback between the atmosphere and fire. This research is necessary to understand such conditions as blowup fires. Scientists at the National Center for Atmospheric Research have coupled a mesoscale weather model and a simple fire behavior model for a dry eucalyptus forest (Clark et al. 1996). This project started only recently, but some interesting results have already been obtained. The researchers have, for example, identified a mechanism that produces parabolic fire fronts. In simulations of an initially straight fire front subjected to a certain range of light winds, the center of the front accelerates preferentially, because the convection column induced by the fire tilts ahead of the front and draws more air from the middle of the fire line than from the ends; hence the windspeed and fire spread are faster across the center. As a result, the fire line takes on the shape of a parabola. Under certain conditions that are still not fully understood, the accelerations of the fire front are rapid and highly localized; the scientists call this event "dynamic fingering." The simulation in figure 3 shows an example of two fingers developing along an initially straight fire line and the attendant wind pattern at a height of 363 feet (110 m). In this case, the wind ahead of the fire is drawn between the fingers, where it opposes the direction of the propagating fire. A critical measure of atmosphere-fire interaction is the ratio of the kinetic energy of the air flow over the fire to the buoyant energy of the heat of the fire. When this ratio is small, conditions are enhanced for a blowup fire. In this case, winds are relatively light over the fire, while the fire itself is energetic. A somewhat counterintuitive finding is that strong winds (high kinetic energy to buoyant energy ratio) stabilize the fire front dynamics, even as they increase the spread rate. Apparently, when windspeeds exceed a critical value, the convective column is displaced too far from the fire front to produce any significant interaction with the fire.

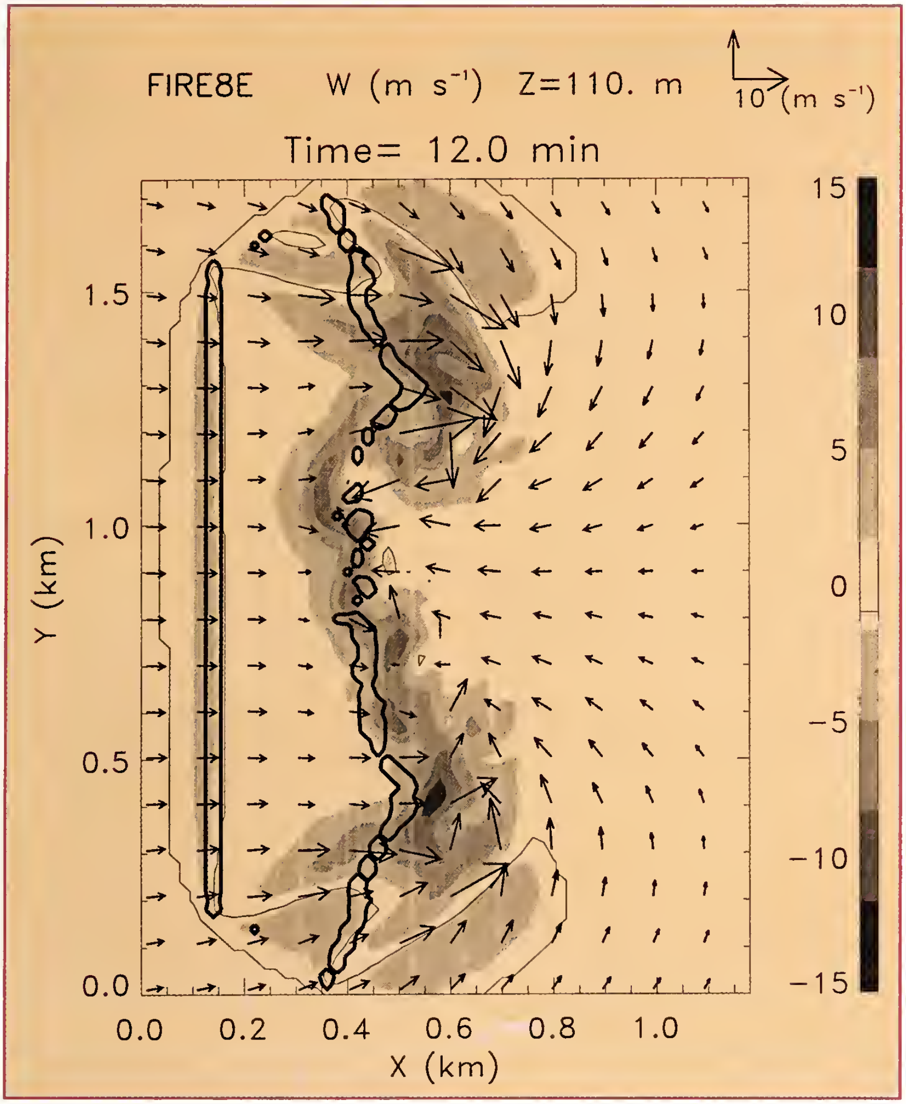

Figure 3—*Simulation from the coupled atmosphere-fire model of Clark et al. (1996). The fire starts along a straight line at the left and develops two dynamic fingers along the 0.4 km (0.24 mi) and 1.3 km (0.78 mi) marks of the y-axis. The gray scale at the right indicates vertical velocity of air flow.*

At this stage, the coupled model is less predictive than it is indicative of the complex interactions that play out between a fire and the atmosphere. It promises significant insight into the processes creating blowups and spotting. All of the models described above, complex as they are, nevertheless are simplifications of reality. At best, model simulations can be expected to resemble the real world only approximately. Fire scientists must describe model uncertainties as definitively as possible, and fire practitioners must understand the limitations of models. We cannot have one without the other, if we are to apply fire weather and fire behavior modeling successfully in fire management.

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Making Sense of Fire Weather

Brian E. Potter

A district ranger checks the local weather conditions and notes high windspeeds. In another district, the ranger sees low relative humidity is predicted for her area. A third ranger looks at the nearest upper-air report and finds strong wind shear and an unstable temperature profile. Which ranger or rangers should consider their observations as indicative of high weather-related fire risk?

The general public and fire managers alike commonly consider a variety of weather-related variables to be indicators of fire risk. These include surface air temperature, windspeed, and humidity. Fire managers and foresters may hear or believe that wind shear and stability also contribute to fire risk. While researchers repeatedly note that various conditions precede or accompany large wildland fires, they have not examined whether these same conditions are equally common on days when no fires occur or when only small or controllable fires occur. When fire managers know which weather-related variables discriminate typical weather conditions from weather associated with large fires, they can prepare for the possibility of a large wildland fire developing.

> When fire managers know which weather-related variables discriminate "large-fire" weather from typical weather conditions, they can prepare for the possibility of a large wildland fire developing.

Methods Used

I analyzed data for 339 large wildland fires that occurred in the Continental United States from 1971 through 1984. Each fire burned 1,000 acres (400 ha) or more. I associated each fire with the nearest upper-air weather station and classified it according to its season (spring, summer, autumn, or winter). I dropped any station and season with fewer than five associated fires from the analysis. Figure 1 shows the number of fires for each station that remained.

For each fire day, I used statistical analysis of variance, a technique that indicates whether or not the fire and typical values are significantly different, to compare the following six measurements with "typical" values for the same station and season:

- Surface air temperature,
- Relative humidity,
- Dewpoint depression,
- Stability,
- Windspeed, and
- Wind shear.

Note that dewpoint depression is the difference between actual air temperature and dewpoint temperature. It is *not* the same as wetbulb depression, which appears on the psychrometric charts in many belt weather kits. Dewpoint depression is always greater than wetbulb depression.

Also note both the size of the wildland fires considered here and the location of the weather observa-

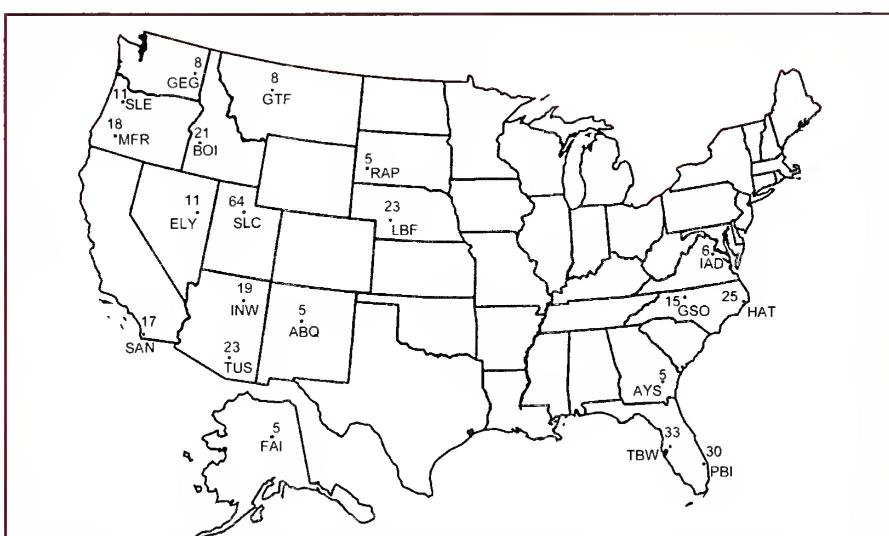

Figure 1—*Locations of stations used for this study and the number of fires over 1,000 acres (400 ha) associated with each station. Three-letter codes are weather station identifiers.*

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tions. The fires are all large fires—the more numerous small fires may show stronger or weaker correlations with some of the weather variables. The observations indicate the weather conditions on a horizontal scale of about 62 miles (100 km). A fire, once started, begins to alter some of these conditions (such as wind), and onsite measurements of any weather variable may differ from measurements taken several miles away from the fire.

Results Found

The results of my analyses show that surface temperature and dewpoint depression are substantially higher on fire days than they are on a typical day for a given location and season. Relative humidity is considerably lower on fire days. Windspeed, wind shear, and stability did not show any significant differences between fire and nonfire days. In other words, it is the more straightforward and commonly known atmospheric properties—high temperatures and low air moisture contents—that most significantly contribute to weather-related fire risk. Thus, the answer to the question in the first paragraph is clear: The second ranger, who saw the forecast of low relative humidity, should be particularly alert to the possibility that the weather will contribute to the development of a large wildland fire.

In examining the six weather variables at individual stations, I found that neither fire-day stability nor fire-day wind shear showed any significant difference from typical values at any of the 20 stations tested. Windspeed proved significant at just two of the stations, relative humidity at four, surface temperature at seven, and dewpoint depression at ten (or half) of the stations. The stations where surface temperature was significant were all west of the Mississippi River.

While they are not a substitute for first-hand experience, these findings can be helpful to fire managers and district rangers. They suggest that the conditions that really matter are those at the surface—stability and wind shear may not be very good fire-weather indicators. Regardless of what part of the country you are in, dewpoint depression is a robust indicator of the weather-related fire risk. Relative humidity, which also measures the moisture in the air, is almost as good and more readily available in weather reports. As experienced fire managers know, even without any measurements or weather reports, they can use their own "senses" to get a good idea what the temperature, humidity, and windspeed are.

With weather measurements, however, fire managers can use the applicable Table 1 to quickly convert relative humidity and temperature to dewpoint depression. This Dewpoint Depression Table (shown both in Fahrenheit and Celsius) can be photocopied, laminated, and kept in belt weather kits for use at any altitude. ■

Table 1—*Dewpoint Depression Table (in both Fahrenheit and Celsius), which can be photocopied, laminated, and kept in belt weather kits. At any altitude, users can quickly convert relative humidity and temperature to dewpoint depression by consulting the applicable version of the Dewpoint Depression Table.*

Dewpoint Depression Table (Fahrenheit)

Temperature (°F)	Relative Humidity (%)							
	10	20	30	40	50	60	70	80
110	69	50	38	30	23	17	12	8
105	68	49	38	29	22	17	12	7
100	66	48	37	29	22	16	12	7
95	65	47	36	28	22	16	11	7
90	64	46	36	28	21	16	11	7
85	63	46	35	27	21	15	11	7
80	61	45	34	26	20	15	11	7
75	60	44	34	26	20	15	10	7
70	59	43	33	25	19	15	10	6
65	58	42	32	25	19	14	10	6
60	57	41	31	24	19	14	10	6

Dewpoint Depression Table (Celsius)

Temperature (°C)	Relative Humidity (%)							
	10	20	30	40	50	60	70	80
44	38	28	21	17	13	10	7	4
40	37	27	21	16	12	9	7	4
36	36	26	20	16	12	9	6	4
32	35	26	20	15	12	9	6	4
28	34	25	19	15	11	8	6	4
24	33	24	19	14	11	8	6	4
20	32	24	18	14	11	8	6	4
16	32	23	18	14	10	8	5	3
12	31	22	17	13	10	8	5	3
8	30	22	16	13	10	7	5	3
4	29	21	16	12	9	7	5	3

SODAR AND DECISIONMAKING DURING THE FORK FIRE

Fred Svetz and Alexander N. Barnett

What does an Incident Meteorologist (IMET) do when anticipating a frontal passage likely to create strong winds and erratic fire behavior during a wildland fire? At the Fork Fire on the Mendocino National Forest in August 1996, the IMET requested an acoustic wind profiler or SODAR (SOund Detection And Ranging) unit. He felt that a SODAR's capability to measure low-level winds continuously would help him monitor expected environmental changes and improve his forecasts.

On the Fork Fire, a SODAR unit assisted personnel with forecasting and decisionmaking. During a weather-driven firestorm that consumed 40,000 acres (16,200 ha) in 6 hours, there were no burnovers, no equipment loses, and no injuries attributed to fire behavior.

What Is SODAR?

The SODAR is a remote-sensing instrument that uses sound to measure windspeed, wind direction, and atmospheric stability up to 2,000 to 3,200 feet (750 to 1,050 m) above the ground at 100 feet (30 m) intervals. It can provide averaged wind data every 5 minutes, every hour, or at other intervals in between.

While other sizes of wind profilers with varying operating or output frequencies are available, the SODAR unit used on the Fork Fire was an AeroVironment Inc. Model 2000 (AV2000),* consisting of

- Three parabolic dish antennas and acoustic drivers mounted on a 30-foot (10 m) trailer (fig. 1).
- A controller unit that houses control electronics, a power amplifier, and a power supply assembly.
- A 486 IBM-compatible computer to run the interface software that logs and processes data and provides the user with both tables and graphs of wind and atmospheric data (fig. 2).

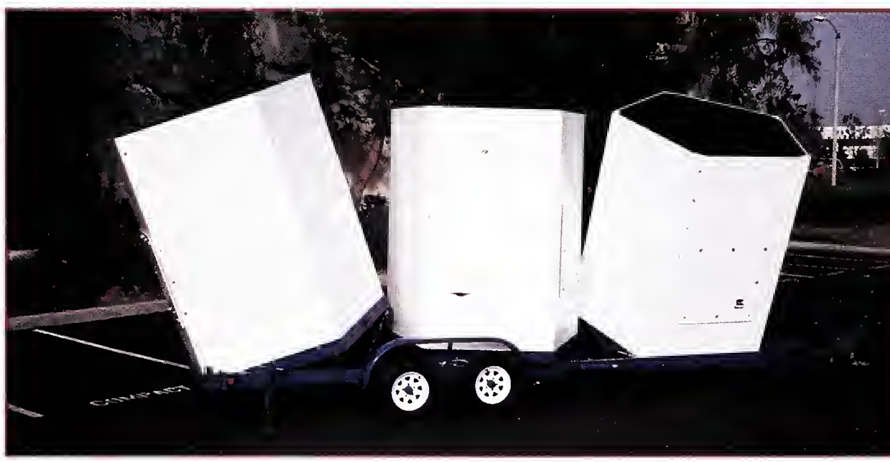

Figure 1.—*The 8-foot- (2.4-m-) tall, foam- and lead-lined wooden enclosures that surround SODAR's antennas and drivers mounted on the trailer that transports them to the field. The enclosures dampen SODAR's sound pulses and reduce the impact of background noises to increase the sensitivity of its measurements. Photo: Ken Underwood, AeroVironment Inc., Monrovia, CA, 1996.*

SODAR Set Up

The SODAR unit was deployed in the extreme northwestern corner of the fire zone, just below the ridge defined in figure 3. The site was 3,200 feet (1,050 m) above sea level in a picnic area on a hillside overlooking the fire zone. This site was selected because

- Background noise levels were low (below 50 decibels).
- There were no physical obstructions in the SODAR beam paths.
- The elevation was adequate to ensure that beam coverage

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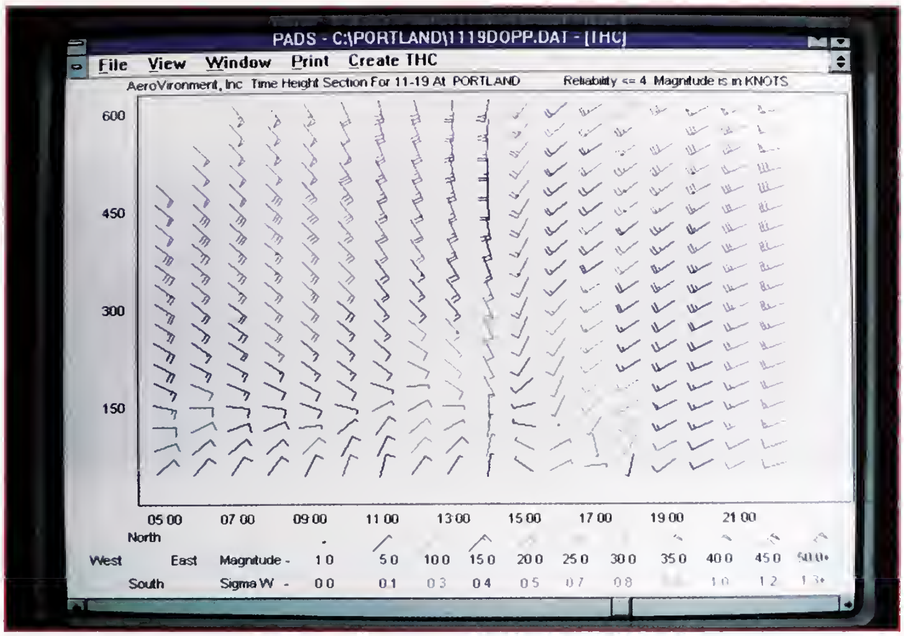

Figure 2.—*Data displayed by a SODAR unit's computer. This graphic shows wind direction and windspeed profiles as displayed on the SODAR computer screen. Each vertical column of wind barbs represents 10-minute averages of the windspeed and wind direction versus height. Windspeed is indicated by the wind barb feathers. Wind direction is indicated by the orientation of the wind barbs. The colors of the wind barbs are an indication of atmospheric stability. Photo: Ken Underwood, AeroVironment Inc., Monrovia, CA, 1994.*

would be representative of the low-level wind flow pattern above the fire.

- It was upwind of the fire zone to help safeguard the operator and to detect changes before they reached the fire zone, thus minimizing burnovers.
- It contained a road adequate for maneuvering a 30 foot (9 m) trailer.

SODAR in Operation

Because the IMET wanted the SODAR to collect data for 24 to 48 hours prior to the arrival of the weather front, SODAR began its measurements at 0900 P.d.t. on August 16. Deploying the SODAR unit well before the arrival of the front meant that the IMET could easily compare baseline weather conditions with changes brought about by the frontal passage.

The SODAR operator and the IMET communicated primarily by cellular phone. Each hour, the SODAR operator called the IMET and read him the windspeed and wind-direction data in miles per hour and degrees for the 10-minute interval occurring just previous to telephoning. The IMET transcribed the verbal windspeed and wind-direction information onto data transfer forms to interpret and use later. As a backup, the SODAR operator also had a command radio, but he used it only when the SODAR noted changes in wind patterns or trends between the hourly cellular contacts or when cellular communications in the remote location were not available. It should be noted that future technological improvements could include the use of radio or satellite phone communications to allow the SODAR's computer to be located where the IMET and Fire Behavior Analysts (FBA's) are preparing their forecasts.

The IMET used the data to develop a "blueprint" of wind patterns and stable layer development and dissipation occurring during a normal daily cycle in the fire zone. The IMET found that weather observations from the fire crew showed excellent agreement with the SODAR data. This confidence in the

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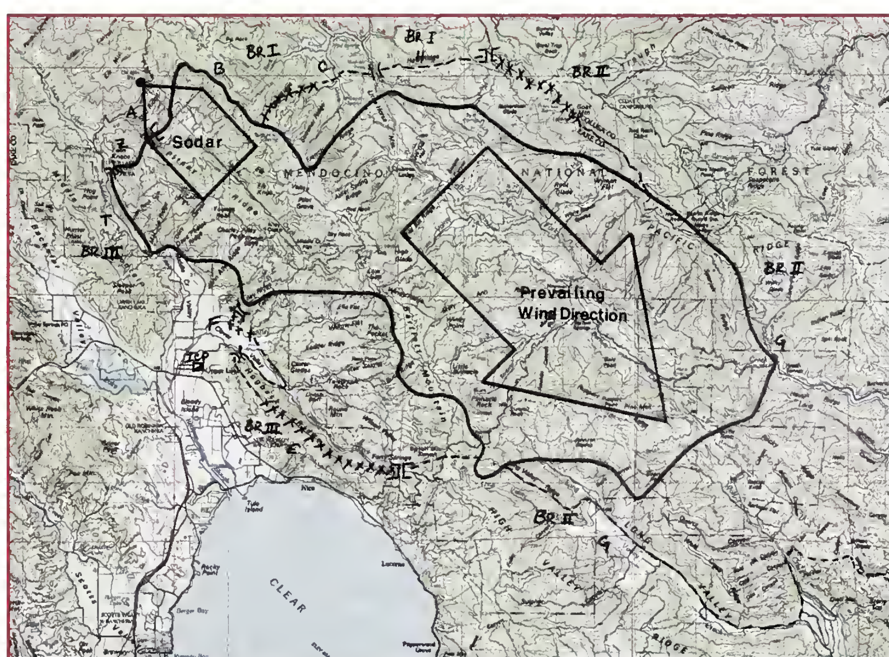

Figure 3.—*Map showing the location of the SODAR unit during the Fork Fire on the Mendocino National Forest in California on August 18, 1996.*

SODAR prompted the IMET to use the observations in the preparation of twice-daily weather forecasts and encouraged the FBA's to use the data in their forecasts as well.

SODAR's Success

When the Incident Command (IC) staff determined that weather and fire behavior forecasts continued to correlate well with actual conditions in the fire zone, their confidence in the IMET's ability increased. On August 18, the day the front was expected, the IMET's forecast was: Morning winds south to west, 4 to 8 mph (6 to 12 kph) with gusts to 14 mph (23 kph), changing in the afternoon to west to northwest winds, 10 to 20 mph (16 to 32 kph) with gusts to 30 mph (48 kph). The confidence of the IC staff in the weather and fire behavior forecasts weighed heavily in their deciding not to assign crews in the expected path of the fire. They held back all fire crews and equipment, except for a limited number of crews assigned to hold the flanks and bulldozer operators constructing fire breaks to save endangered communities.

A view of the SODAR model being used 3,200 feet (1,050 m) above sea level in a picnic area on a hillside overlooking the Fork Fire in August 1996. Photo: Alex Barnett, AeroVironment Environmental Services Inc., Monrovia, CA, 1996.

Each SODAR antenna consists of a parabolic dish that faces upward with an acoustic driver mounted above each dish pointing downward. By emitting a sound pulse at a known frequency and monitoring the Doppler shift of the return echoes, the instrument calculates the windspeed and wind direction at various altitudes. Photo: Jeff Bradley, AeroVironment Inc., Monrovia, CA, 1996.

One hour before the weather front's arrival, the SODAR detected increasing windspeeds at the level of the ridge tops (approximately 1,000 feet (330 m) above the average elevation of the fire). This 1-hour warning gave the IC staff time to move remaining fire crews and equipment out of danger from the expected runs. Within the next 6 hours, an explosively developing firestorm consumed 40,000 acres (16,200 ha). Yet during this period, there were no burnovers, no equipment losses, and no injuries attributed to fire behavior.

Results of SODAR Use

The SODAR unit proved to be a valuable tool for characterizing wind and stability patterns that influenced fire behavior on the Fork Fire. It provided the IMET with a rare opportunity to gather quantitative low-level wind data on a near real-time basis. The consistency and reliability of these data from an area immediately adjacent to the wildfire (compared to occasional surface observations from spotters in the field) made it possible to verify wind forecasts for the fire area, which in turn increased the IMET's confidence in the accuracy of his forecasts and prevented misanalysis of the low-level wind field.

The IC staff also gained confidence in the forecasts. As a result, they placed greater emphasis on them when planning their fire suppression strategies. SODAR data helped to provide them with an objective basis for their decisionmaking concerning the expected erratic fire behavior during the frontal passage and helped to give an additional margin to ensure firefighter safety.

The Future

We hope that the success of the SODAR at the Fork Fire will open discussions among IC staffs nationwide concerning how this technology can regularly be incorporated into wildland fire suppression strategies. When erratic fire behavior is occurring or expected, a SODAR can be a resource to assist the IMET with forecasting and IC staffs with their decision-making. When erratic fire behavior is not expected, a SODAR can be considered for temporary (24 to 48 hour) deployments to characterize daily wind and stability patterns in the fire area both during wildland fires and prescribed burns.

We anticipate that the incorporation of radio- or satellite-data transfer technology and the use of existing single-antenna SODAR units will improve the rapid deployment and portability of the units to and in the field. This will make SODAR more effective in providing wind and stability data in the future.

For more information about how SODAR units measure windspeed, wind direction, and atmospheric stability and their possible future uses during other wildland fires or during prescribed fires, readers should contact Alex Barnett; telephone 818-357-9983, fax 818-359-9628, or e-mail barnett@aerovironment.com ■

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